Non-Linear Dynamics in Spin Liquids

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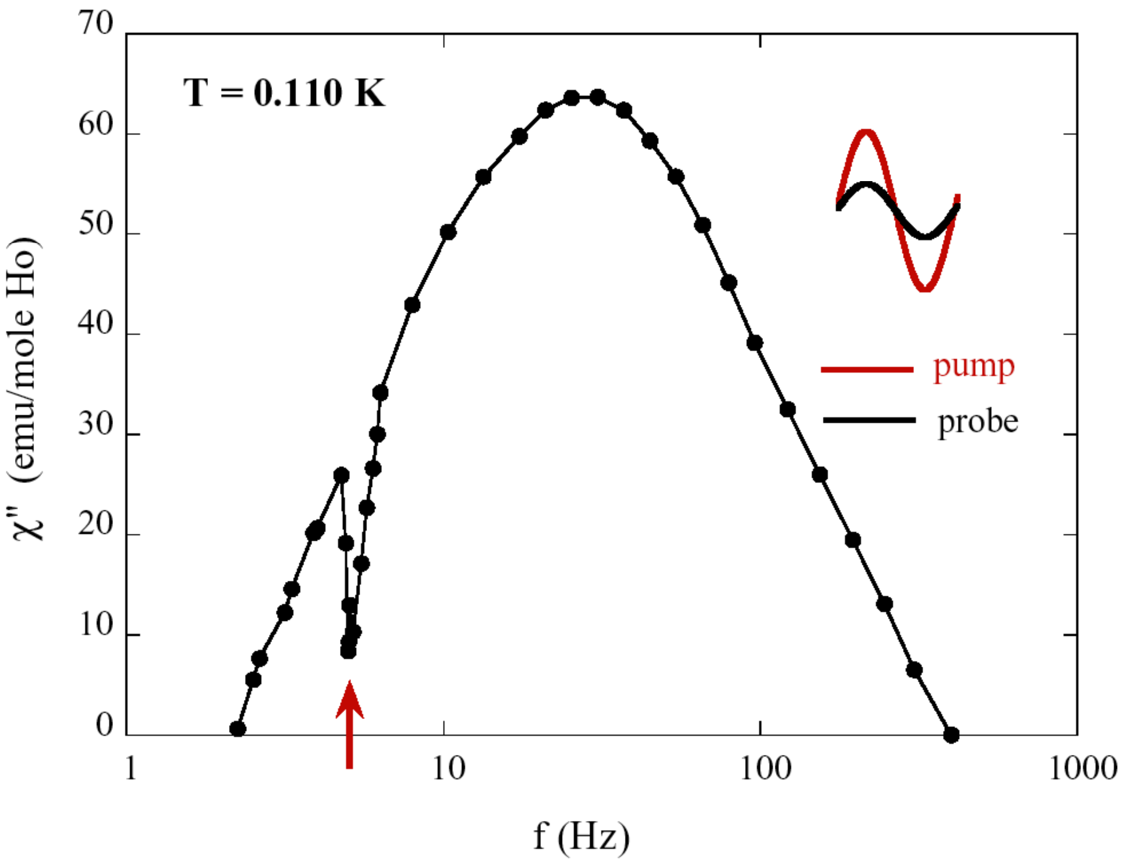
Magnetic solids offer arrays of quantum degrees of freedom – spins – interacting with each other in a manner and strength limited only by the ingenuity of synthetic chemists. The outcome of this chemical tunability is a plethora of collective phenomena, ranging from the simple ferromagnetism of iron and nickel to the nano-antiferromagnetism of vortices in certain high temperature superconductors. The large variety, many possible ground and excited states, and ease of handling make magnetic solids attractive candidates as building blocks for quantum computers. Unfortunately, there is a large barrier to exploiting quantum effects in magnetic solids: namely, the absence of coherence effects that can be simply manipulated and observed. In particular, it is difficult to create the magnetization oscillations corresponding to prepared superpositions of states, which are so straightforwardly created in liquid phase nuclear magnetic resonance (NMR) experiments.

We have discovered that spin liquids, stabilized both by quantum fluctuations ($LiHo_{0.045}Y_{0.955}F_4$) and by geometrical frustration (Gadolinium Gallium Garnet), self-organize into coherent oscillations of hundreds of spins labeled by frequency when driven from equilibrium, thereby providing an alternative paradigm for quantum computation to that based on single, spatially separated qubits. The excited spins are removed from the magnetic relaxation spectrum in a process known as “hole burning” in optical bleaching experiments (see Figure below for $LiHo_{0.045}Y_{0.955}F_4$), but we use an inductance loop at a few Hertz rather than a laser at TeraHertz frequency, with an excitation field a fraction of the earth’s magnetic field. The resulting magnetic excitations retain phase coherence with the pump pulse for ten seconds after the pump is turned off, returning to their ground state via a process paralleling free induction decay in NMR experiments. Finally, we find that it is possible to simultaneously burn holes at different frequencies, making it possible to encode independent bits of information in the non-interacting eigenstates of the system.

The description of the spin clusters – akin to Rabi oscillations of the clusters in the weak transverse mixing fields that arise from the anisotropic Ho dipole interaction – follows from a simple analysis of the non-linear response. The magnetization saturates by 1 Gauss and follows the familiar Brillouin form for Ising spins, $M \sim \tanh(mh_{ac}/k_BT)$. Unlike a simple paramagnet, m here is not the magnetic moment of a single Ho ion, but rather the total moment of the spins locked together in the cluster. Analysis of this non-linear response finds that the clusters responsible for the saturation and hole burning effects at T = 0.110 K and f = 5 Hz contain approximately 260 spins. This corresponds to cluster dimensions of approximately 6 Ho-Ho spacings on a side, and a probability of cluster membership of 1% for any given spin in the crystal, comparable to that deduced from the spectral weight carved out by the hole.

True insight into the organization of the clusters, however, awaits real-space imaging via scattering or related techniques. Such an accomplishment would not only be important in revealing the ways correlated, quantum systems pick between multiple, potential ground states, but it is an essential component in understanding their predilection to organize themselves on the nanoscale.



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